

The Local Galaxy Density and the Bulge-to-Disk Ratio of Disk Galaxies

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Abstract

Relying on samples of disk galaxies for which a detailed photometric bulge/disk decomposition has been provided in the literature, we examine the dependence of the bulge-to-disk luminosity ratio (B/D) on the blue absolute luminosity and on the environmental density. In our statistical analysis of various B/D data sets we pay particular attention to disentangling the role played by the galaxy morphology–galaxy density relation. Besides, we focus our attention on nearby ($z < 0.01$) galaxies, for which we can provide a three-dimensional characterization of the local galaxy density.

We find that the observed tendency of galaxies to have greater B/D with increasing galaxy density simply reflects the average decline of B/D towards later morphological types together with the morphology–density relation. This relation tends to give rise also to a greater proportion of bright bulges in denser regions, because the decrease of B/D towards later types is mostly due to a dimming of the bulge rather than to a brightening of the disk. But when we remove the effect induced by the morphology–density relation, we detect no clear evidence of a dependence of B/D on galaxy density. Furthermore, B/D turns out to be substantially unrelated to the blue absolute magnitude of the galaxy. We briefly discuss to what extent our results (partially) disagree with previous claims.

Subject headings: galaxies: clustering — galaxies: structure

1 Introduction

A major task of the theories of galaxy formation and evolution is to account for the distinct components into which the galaxy light distribution can be divided, the most prominent components being the bulge and the disk. Much work has been devoted to the photometric separation of bulge and disk light contributions and to the study of the main structural properties of these components (see, e.g., the reviews by Simien, 1988, and by Capaccioli & Caon, 1992). However, insufficient attention has been paid to exploring the influence of the galactic environment on these properties, in particular on the bulge-to-disk luminosity ratio (hereafter B/D); this quantity tends to decrease towards later morphological types as a natural consequence of the Hubble classification criteria. The Hubble morphological sequence from early to late types is largely a sequence of increasing dominance of disk over bulge. But the weakness of the dependence of B/D on morphological type (see §2 below) in practice makes it impossible to view the Hubble morphological sequence simply as a B/D sequence only.

From an analysis of his own estimates (Dressler, 1980a) of the total and bulge magnitudes of a very large sample of cluster galaxies, Dressler (1980b) noted that, for both lenticulars and spirals, B/D and bulge luminosity (though not total luminosity) show a positive correlation with the local projected galaxy density (computed for each galaxy on the basis of the area encompassing the ten nearest projected neighbors). Considering also a nearly complete magnitude-limited sample of field galaxies, Schechter & Dressler (1987) confirmed that cluster galaxies have greater B/D than field galaxies; furthermore, they reported a strong positive dependence of B/D on the galaxy blue total luminosity for generic samples of cluster and field galaxies; this relation was found to be weaker for spirals alone.

Later, Solanes, Salvador-Solé & Sanromà (1989) reanalyzed Dressler's (1980a) data, subdividing disk galaxies into four morphological types (S0, Sa, Sb, Sc). They noted a significant B/D–absolute magnitude correlation, especially for late types (Sb and Sc), with brighter galaxies having an average lower B/D (i.e., contrary to the claim by Schechter & Dressler (1987)). Besides, they emphasized that the claimed environmental density effects on B/D simply reflect the well-known morphology–local density relation (see, e.g., Whitmore, Gilmore & Jones, 1993, and Whitmore, 1990), which holds true also within spirals (e.g., Giuricin et al., 1988; Tully, 1988b), owing to the average decline of B/D towards later morphological types. In other words, the fact that earlier types, which have greater B/D, preferentially reside in denser regions would create a B/D–environmental density correlation as a secondary effect, which would vanish within subsets of objects of a given morphological type.

In the present paper we wish to address all these issues, viz. the relations of B/D to absolute magnitude and to environmental density at both small and large scales (large-scale effects have not yet been investigated in the literature). For this purpose we shall rely on the galaxy samples with available bulge/disk decomposition provided by Kent (1985, 1986, 1988; hereafter K85, K86, K88), Simien & de Vaucouleurs (1986), (SdV), Kodaira, Watanabe & Okamura (1987) (KWO). These samples, albeit much smaller than Dressler's (1980a), are characterized by a detailed bulge/disk decomposition, a much finer and more reliable morphological classification, a more accurate galaxy apparent optical magnitude, and a better knowledge of galaxy environment and distance (the redshift is known for all galaxies, whilst redshift incompleteness is large in Dressler's (1980a) sample). They comprise mostly bright and nearby galaxies, which span a rather wide range of environmental density (from the Virgo cluster to the low-density regions of the Local Supercluster). We have also taken into consideration the data sample provided by Andredakis & Sanders (1994) (AS), which, however, contains a small number of objects.

In §2 we describe the data samples used and our parameters for local galaxy density. In §3 we present our analysis of the B/D data. The conclusions are reported in §4.

2 The Data Samples

2.1 The B/D data samples

Most of the classical methods of bulge–disk photometric decomposition rely on fundamental differences in the light profiles or the intrinsic flattenings of the two components. Adopting standard laws for the light distribution of the bulge and disk components (i.e., a de Vaucouleurs $r^{1/4}$ and an exponential law, respectively), K85 employed mostly a standard non-linear least-squares fit to the main axis profiles of 105 disk galaxies. For a few objects he used the iterative decomposition method described by Kormendy (1977), in which one solves for the disk parameters in a region where disk light dominates, and likewise for the bulge parameters. At each iteration, the light from the component being kept fixed is subtracted from the total luminosity profile before the other component is solved for. The process is iterated until convergence is achieved. In his subsequent photometric study of 37 Sb and Sc objects (K86), without making any assumption regarding the fitting laws for either component, the author assumed that each one is characterized by elliptical isophotes of constant, and essentially different, flattening; then, an iterative process yielded the bulge and disk profiles. Later, following one of the two approaches used in his previous studies, Kent (1988) reported the luminosity–profile decomposition of another 14 spirals. Kent (1985, 1986, 1988) reduced his photometric measures to the r band of the *uvgr* system of Thuan & Gunn (1976). We have also assembled together the K85, K86, K88 data in order to obtain the fairly homogeneous global Kent (K) sample.

SdV slightly modified Kormendy’s iterative decomposition procedure in order to allow a better handling of individual luminosity profiles. Fitting the above-mentioned standard laws to the light profiles, SdV provided new results for 32 galaxies and collected results on 66 additional objects from previous papers. They homogenized the merged set of B/D in the B band by making some corrections to the original B/D values in a few cases for which the results of various authors showed systematic differences.

Without resorting to an initial guess for the bulge and disk parameters, KWO generated a grid of models with different combinations of scale parameters; from among these they selected the ten best-approximating models, consisting of a standard spheroid and a standard disk. Later, they made a search among these models to identify the one giving the best fit to the observed profile. KWO presented structural parameters (in the V band) of 167 galaxies which are probable members of the Virgo cluster and the Ursa Major cloud. Their galaxy sample is nearly complete for large and bright galaxies ($\log D_{26}(0.1') \gtrsim 1.3$ and $V_{26} \lesssim 14 \text{ mag}$) in these two sky areas.

Furthermore, AS reanalyzed the K86 observational data by means of different decomposition schemes; they applied a standard non-linear two-component (bulge and disk) simultaneous fitting to the observed light profile. Besides modeling spirals by an exponential disk and a $r^{1/4}$ -law bulge, the authors also attempted to decompose spirals in terms of an alternative model, consisting of an exponential disk and an exponential bulge; they concluded that the double-exponential model is superior in many statistical aspects of the fitting procedure for the bulges of mid- and late-type spirals. The two sets of B/D values which result from the two approaches are hereafter referred to as AS1 and AS2, respectively.

In the present study we consider the lenticulars and spirals of the galaxy samples mentioned above. More specifically, we shall mainly analyze the homogeneous samples SdV, KWO, K. Omitting from the KWO sample the galaxies with low-quality spheroids and disks (i.e., with respective weights $w = 2$ and $w < 4$, as tabulated by KWO in their Table 2), we also construct a homogeneous subsample of good quality data (hereafter referred to as KWO’ sample). We also examine samples K85, K86, K88, AS1, AS2, which, however, include a small number of objects. In the case of multiple entries for a galaxy, we adopt the mean values of B/D. In the statistical analysis described in the following section, more confidence should be given to the spirals of the K sample than to the whole S0+S K sample, because K85 regarded his own decompositions resulting in $B/D > 1.70$ as particularly dubious (objects with such a great B/D are generally ellipticals or lenticulars). The B/D data given by SdV and K85 are corrected for internal absorption; the other data sets are uncorrected, but the authors generally avoided observing strongly inclined objects.

2.2 Comparison between different samples

The comparison between different data samples is not an easy task, because of the inhomogeneity of photometric measures, which are taken in different spectral bands, and even more because of the different photometric decomposition procedures (although some attempts to merge different samples will be made in the following section). The inhomogeneity of different data samples is illustrated in Table 1 and Fig. 1. Table 1 reports the means, standard deviations s.d., medians, associated 90% confidence intervals of the B/D distributions of samples SdV, K, KWO, KWO', AS1, AS2 for various morphological types. Fig. 1 shows the plot of the medians of B/D (and of associated 90% confidence intervals) versus morphological type, for samples SdV, K, KWO, KWO'. We have verified that colour differences alone cannot account for the differences in the B/D data sets; thus, the observed basic differences between different B/D samples are to be mainly ascribed to systematic effects in photometric decomposition techniques.

In the following lines we briefly comment on the most pronounced differences between different B/D samples (see, e.g., Simien (1988) for further details). The B/D distributions (as well as structural parameters) derived by K and SdV are in broad agreement for lenticulars and early-type spirals; for late types, SdV found typically greater B/D values than K did. For late-type spirals, KWO found bulges of systematically larger effective radii and luminosities, but lower effective brightnesses than SdV and K85 did (see, e.g., Simien, 1988). As a consequence, their (typically greater) B/D values show a weaker tendency to decrease along the Hubble sequence with respect to the SdV and K data. However, the KWO' subset of good quality data shows better agreement with the SdV and K data. With their new double-exponential model, AS2 drastically reduced the range of values spanned by the structural bulge parameters (effective radius and surface brightness). The smaller scale lengths and fainter effective surface brightnesses which result from their alternative bulge model also led to smaller bulge luminosities and B/D values. For mid- and late-type spirals, the AS2 B/D data are in closer agreement with K86 than the AS1 data are (whilst for early-type spirals the AS2 data seem unreasonably low.)

In general, B/D, bulge and disk luminosities are thought to be more reliably determined than the structural parameters of the two components (e.g., Schombert & Bothun, 1987), which are therefore not analyzed in the present paper. Remarkably, in all the samples considered, the typical decrease of B/D towards later types is due much more to a drop in bulge luminosity than to a brightening of the disk (as was in general already noted by the authors of the photometric decompositions). This important point will be discussed in the last section.

There are 12 galaxies (9 spirals) common to the SdV and K samples. The standard deviations of the differences between the B/D values of the galaxies in common are s.d.=2.57 and 0.54, for the 12 disk galaxies and 9 spirals, respectively. These observed standard deviations can be compared with the respective values of s.d.=2.02 and 1.38, which are the standard deviations which would be expected if the whole scatter in B/D (as represented by the standard deviations tabulated in Table 1) were due to errors in the determination of B/D. We evaluate the expected standard deviations as the square roots of the weighted mean variances, taking weights equal to the proportions of common objects of various morphological types. An analogous exercise for the 30 spirals common to K86 and AS1 (K86 and AS2), who analyzed the same photometric data in different manners, leads to the observed value of s.d.=1.00 (s.d.=0.51) — which is due to differences in decomposition only — as against the expected value of s.d.=1.18 (s.d.=0.66). For the 19 objects (9 spirals) common to the SdV and KWO samples, we obtain observed values (s.d.=1.28 and s.d.=0.19) which are definitely smaller than the expected values (s.d.=1.90 and s.d.=0.77). The same holds true for 11 objects (7 spirals) common to the SdV and KWO' samples, for which we obtain the observed values of s.d.=1.24 and s.d.=0.18 as against the expected values of s.d.=1.57 and s.d.=0.56.

We conclude that most of the dispersion in B/D is due to errors in decomposition (with slight contributions from errors in photometry and morphology classifications). But there is certainly some cosmic scatter in B/D (for spirals in all samples and for lenticulars in at least some samples). Thus, we may well wonder whether environmental density can be a major source of intrinsic scatter in B/D.

2.3 The environmental density

As already done in recent studies on the environmental effects on bars (Giuricin et al., 1993), arm classes (Giuricin et al., 1994), and nuclear activity (Monaco et al., 1994), we use the Nearby Galaxy Catalog (Tully, 1988a; NBG) to give a three-dimensional definition of the environment. This catalogue is intended to include all known nearby galaxies with systemic velocities lower than 3000 km s^{-1} , which corresponds to a distance of 40 Mpc with the Hubble constant $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (the value adopted throughout the present paper). In the NBG every galaxy is assigned a distance based on its redshift, on the assumed value of H_0 , given before, and on corrections for group membership and Virgo infall (according to the Virgo-centric retardation model described by Tully & Shaya, 1984). Every galaxy member of a group or cluster is given a distance consistent with the mean velocity of the system itself.

Following Tully (1988b) in the main, with this spatial distribution of galaxies we define the parameter ρ_σ of local galaxy density (where ρ_σ is in units of galaxies per Mpc^3) as the number of galaxies per Mpc^3 that are found around every galaxy within the smoothing length σ (in Mpc):

$$\rho_\sigma = \sum_i C \exp[-r_i^2/2\sigma^2] \quad (1)$$

where every galaxy is smoothed with a gaussian filter of half-width σ , r_i is the spatial distance of the i -th galaxy from the specified galaxy and the normalization coefficient is $C = 1/(2\pi\sigma)^{3/2} = 0.0635/\sigma^3$; the sum is carried out for all galaxies except the one we are calculating the density for. In order to correct the density for incompleteness of NBG at large distances, we weight every galaxy with a correction factor $F(\mu)$, where $\mu = 5 \log D + 25$ is the distance modulus and D is the distance in Mpc. F expresses the number of galaxies (brighter than $M_B = -16$) that exist for every galaxy catalogue. We use the following expression for F :

$$F = \exp[0.033(\mu - 28.5)^{2.83}] \quad (2)$$

(and $F=1$ when $\mu < 28.5$). Finally, our density parameter, corrected for incompleteness, is

$$\rho_\sigma = \sum_i C F(\mu_i) \exp[-r_i^2/2\sigma^2]; \quad (3)$$

ρ_σ gives the number of galaxies, per Mpc^3 , brighter than $M_B = -16$ around the galaxy considered (see Monaco et al., 1994, for the evaluation of $F(\mu)$ and ρ_σ).

As discussed in Giuricin et al. (1993), because of the clustering properties of galaxies, the choice of different σ -values implies a different physical meaning for the local galaxy density ρ_σ , so that a dependence of a quantity on ρ_σ with low (high) σ -values refers to small- (large-) scale density effects. Border effects make less reliable the estimates of ρ_σ for objects which lie close to the limiting distance of the NBG sample; however, there are only a few NBG galaxies lying at distances greater than 36 Mpc in our samples (i.e., one, six, and two objects in the SdV, K, KWO and KWO') samples, respectively). In any case, we have checked that the omission of these few objects does not substantially change the results presented below (§3).

In the present paper we have updated the galaxy morphological types by consulting the Third Reference Catalogue of Bright Galaxies by de Vaucouleurs et al. (1991) (RC3).

3 Analysis and Results

First, we analyze separately the lenticulars and spirals (S0+S) of the homogeneous samples SdV, KWO, KWO', K. The analysis of samples K85, K86, K88, AS1, AS2 does not yield interesting results, because of poor statistics. We shall also attempt to merge different B/D samples. Basically, we consider those objects (lenticulars and spirals) which are included in NBG and we repeat the analyses for the subsets of

spirals (S) and spirals having morphological types from T=0 to T=5; this is roughly the T range where usual photometric decomposition techniques are thought to be more accurate, since both bulge and disk contributions are important (see, e.g., the methodological discussion by Schombert & Bothun, 1987).

In the following discussion of our correlation analysis, we shall present only the most interesting results in some tables and we shall mention the cases for which we obtain significance correlations. In the discussion we shall not bother with correlations at the (one-tailed) <95% significance level (which corresponds to the <90% level for a two-tailed test).

3.1 The B/D- ρ_σ and T- ρ_σ correlations for homogeneous samples

In order to investigate whether environmental density influences B/D, we primarily deal with the B/D- ρ_σ correlations (with $\sigma=0.25, 0.5, 1, 2$ Mpc) taking into account the correlation of B/D with galaxy morphological type T (coded as in RC3). We analyze the significance of the correlations between two variables by computing the two non-parametric rank correlation coefficients, Spearman's r_s and Kendall's r_k (see, e.g., Kendall & Stuart, 1977). In order to estimate to what extent the B/D- ρ_σ correlations are spuriously induced by the morphology-density (T- ρ_σ) relations, whenever the latter correlations are statistically significant, we calculate Kendall's partial correlation coefficient r (e.g., Siegel, 1956). This is a measure of the correlation between two data sets (B/D and ρ_σ , in our case) independently of their correlation with a third data set (T, in our case). Since the sampling distribution of r is unknown, we adopt the bootstrap method of resamplings (e.g., Efron, 1979; Efron & Tibshirani, 1985) in order to compute its statistical significance (we performed 5000 bootstrapping resamplings for each correlation). We calculate the partial correlation coefficient r and its statistical significance when the T- ρ_σ correlation is significant (at the >90% confidence level).

In Table 2 we present the results of the most interesting cases; we list the two correlation coefficients r_s and r_k , together with the associated (one-tailed) percent significant levels for the correlations of B/D versus ρ_σ (with $\sigma=0.5$ Mpc) and of T versus ρ_σ (with $\sigma=0.5$ Mpc). The correlations involving ρ_σ with $\sigma=0.25, 1$, and 2 Mpc lead to similar results.

We note that the expected T- ρ_σ correlations turn out to be very significant within wide samples (SdV, KWO, KWO') of S0+S objects (they are perhaps present also within the SdV spirals). These correlations indicate that earlier types preferentially reside in denser regions than later types. Poor statistics probably prevent the appearance of the morphology-density relation in the other, generally smaller, samples. (For the K sample there are few objects which reside in high-density regions.) Also the B/D- ρ_σ correlation is very strong within wide samples (SdV, KWO, KWO') of S0+S objects and marginal within KWO' spirals. Figs. 2 and 3 show the B/D- $\rho_{0.5}$ correlations for the S0+S objects of the SdV and KWO samples. Since various morphological type intervals are denoted by different symbols, Figs. 2 and 3 also show the T- $\rho_{0.5}$ correlations.

In general, the degree of correlation between B/D and ρ_σ appears to be similar to that between T and ρ_σ ; thus, the partial correlation coefficient r turns out to be consistently not significant, except for the KWO' sample, where the B/D- ρ_σ partial correlations (for all four σ -values) turn out to be weakly significant (on average, at the $\sim 95\%$ significance level).

We conclude that there is no sure evidence of a true B/D-local density correlation cleared of spurious secondary dependences related to the morphology-density relation.

3.2 The B/D- ρ_σ and T- ρ_σ correlations for combined samples

We try to build a large sample, combining the SdV, KWO, KWO' and K samples. To do this, first we multiply all K, KWO, KWO' B/D values by suitable conversion factors; these, for each morphological type interval, are taken to be the ratios of the medians of the K, KWO, KWO' values of B/D with respect to the corresponding medians of the SdV values (see the medians tabulated in Table 1). For galaxies which are common to two of the three samples, we chose the B/D values given by SdV and K,

in this order of preference. In this manner, for each morphological type interval, we construct K, KWO, KWO' B/D distributions, which by definition have the same medians as the respective SdV distributions, although they may still have a different shape. Then, we check that the K normalized B/D distributions are not statistically different from the corresponding SdV distributions (for each type interval and for all types together) by applying the classical Kolmogorov-Smirnov test (e.g., Hoel, 1971), the Rank-Sum test (e.g., Hoel, 1971), and the Mann-Whitney U-test (e.g., Kendall & Stuart, 1979). The same holds true for the comparison between the KWO, KWO' normalized and SdV distributions. But we realize that the KWO and K normalized distributions are statistically indistinguishable only for earlier types ($T < 3$), whereas the inclusion of later type objects makes the two distributions different (e.g., at the 94.3%, 97.3%, 98.3% levels for the respective intervals $T < 4$, $T < 5$, $T < 6$, according to the Kolmogorov-Smirnov test). Analogously, as objects of later types are included, the KWO' and K normalized distributions become different (e.g., at the 96.0%, 93.4%, 90.3% levels for $T < 4$, $T < 5$, $T < 6$). Therefore, deeming it unreasonable to combine samples K and KWO (or KWO'), we deal with the combined samples SdV+K, SdV+KWO, and SdV+KWO' only.

Table 3 presents the correlation analysis of some combined samples. With respect to the previous analysis of individual samples, combined samples generally show more significant B/D- ρ_σ and T- ρ_σ total correlations (also for spirals) because there are more objects, but no appreciable B/D- ρ_σ partial correlations (not even for combined samples involving KWO'). This confirms that there is no evidence of a true dependence of B/D on local density, whenever the effect induced by the morphology-density relation is removed.

In order to enlarge our samples with the inclusion of non-NBG galaxies, we provide a further, rough characterization of environmental density, assigning a parameter ENV to each NBG and non-NBG galaxy. ENV is defined as an integer which grows with the increasing probability of being a member of the Virgo cluster. First, we simply assign ENV=0 to non-Virgo objects and ENV=1 to Virgo members (according to Binggeli, Sandage & Tammann, 1985). Then, we reassign ENV=1 to objects located in the peripheral regions of the Virgo cluster (like the Virgo southern extension and the Virgo clouds W, W', M), and ENV=2 to members of the main body of the Virgo clusters (Virgo subclusters A and B) (see also Binggeli, Popescu & Tammann (1993) for membership assignments in the Virgo region.). In substantial agreement with the outcomes of our previous analyses, we can state that there is no clear evidence of a true B/D-local density correlation in homogeneous and combined samples, whenever we remove the effect induced by the morphology-density relation.

3.3 The B/D- D_v and T- D_v correlations

In a search for large-scale environmental effects on B/D, an interesting quantity is the galaxy spatial distance D_v (in Mpc) from the center of the Virgo cluster. As already done in Monaco et al. (1994), we use D_v to explore effects on large scale in the Local Supercluster. Note that D_v , being a three-dimensional distance, is meaningful mainly outside the Virgo cluster. We subject our samples to analysis of the B/D- D_v total correlations and (T-independent) partial correlations. Table 4 presents the results for the most interesting cases. We detect appreciable T- D_v correlations in wide samples (S0+S objects of the SdV and KWO samples, K spirals, and combined samples which involve these data sets; earlier types are typically closer to the Virgo cluster center (as is expected from the morphology-density relation). This correlation gives rise to appreciable B/D- D_v total correlations; however, the partial correlation coefficients are, in general, not significant. Fig. 4 shows the B/D- D_v correlation for the S0+S objects of the KWO sample. Since various morphological type intervals are denoted by different symbols, Fig. 4 illustrates also the T- D_v correlation. Both correlations are essentially due to Virgo galaxies; this means that the observed effect is essentially present on a scale of a couple of Mpc, in agreement with the general morphology-clustercentric relation (Whitmore et al., 1993). We note that in the Virgo cluster region the B/D- D_v correlation, while giving essentially the same information as the B/D- ρ_σ one, is typically weaker. On the other hand, no effect is observed on larger scales.

From this analysis we conclude that there is no unambiguous evidence that B/D is related to the distance from the Virgo cluster, irrespective of the tendency induced by the morphology–density relation.

3.4 The $M_{bu}-\rho_\sigma$ and $M_d-\rho_\sigma$ correlations

We wish to check whether the absence of significant B/D– ρ_σ correlations is simply due to the lack of both bulge–absolute magnitude ($M_{bu}-\rho_\sigma$) and disk–absolute magnitude ($M_d-\rho_\sigma$) correlations rather than to a suitable combination of these two correlations (as, e.g., a parallel dependence of M_{bu} and M_d on environmental density). A similar argument holds for the B/D– D_v and B/D–ENV correlations. In order to cast light on this question, we undertake an analysis of the $M_{bu}-\rho_\sigma$ and $M_d-\rho_\sigma$ correlations. We consider only the samples SdV, KWO, KWO', because, for many objects of the SdV sample and all galaxies of the KWO (KWO') sample, the values of M_{bu} and M_d can be directly estimated from the tabulated structural parameters and the adopted distance (not from B/D and galaxy absolute magnitude, which would amplify the uncertainties on M_{bu} and M_d). We analyze the S0+S, the S objects, and two other type intervals, where the estimates of M_{bu} and M_d are respectively expected to be most reliable, namely lenticulars and early-type spirals (up to T=3) for M_{bu} and mid/late-type spirals (T>2) for M_d . We include also objects with unknown B/D, but known M_{bu} or M_d . We construct the KWO' sets of M_{bu} and M_d data by eliminating from the KWO sample galaxies with low-quality spheroids and disks (as explained in the previous section). The M_{bu} and M_d values of the SdV sample are corrected for Galactic and internal absorption (according to the precepts described by SdV). The M_{bu} and M_d values of the KWO and KWO' samples are uncorrected for these effects; however, all objects lie in sky areas characterized by similar Galactic absorption and are not strongly inclined.

Table 5 reports some results relative to the $M_{bu}-\rho_\sigma$, $M_d-\rho_\sigma$ correlations for S0+S objects. The partial $M_{bu}-\rho_\sigma$ correlations (at fixed T) are never significant, although the total ones are significant in some cases (for the S0+S objects of the SdV and KWO samples). In other words, in the latter cases a dependence of M_{bu} on environmental density is induced by the morphology–density relation as well as by the pronounced dimming of bulges towards later types within the SdV and KWO samples. No total/partial $M_{bu}-\rho_\sigma$ correlations are observed within the other type intervals.

We find no total or partial $M_d-\rho_\sigma$ correlations within the SdV sample. We see an appreciable effect in the S0+S objects of the KWO and KWO' samples at a relatively large scale (mainly for the parameter $\rho_{2.0}$). No effects are detected within the other type intervals. In the case of M_d , because of the insignificant or much weaker dimming of the disks with respect to the bulges towards later types in the samples considered, the morphology–density relation does not appreciably affect the total $M_d-\rho_\sigma$ correlations; i.e., it does not give rise to appreciable negative total $M_d-\rho_\sigma$ correlations. We have verified that the opposite (i.e. positive) effect is induced by the observation selection of the galaxy sample. Specifically, within a magnitude-limited galaxy sample which covers mostly the Virgo sky area, the galaxies which lie behind the main Virgo cluster concentration, in low-density zones, tend to be, on average, more luminous than their nearby (Virgo cluster member) counterparts; they will also have, on average, brighter disks. As a matter of fact, we have checked that all partial correlations disappear when we restrict the samples to objects lying at a distance smaller than 25 Mpc, which minimizes the effects of observational selection (see Table 5).

We have verified that the correlations between M_{bu} (M_d) and the other environmental indices D_v and ENV yield consistent results.

To sum up, we find different behaviours of M_{bu} and M_d with the various environmental indices. The basic difference is to be ascribed to the influence of the morphology–density relation. In samples covering a wide morphological interval, this relation alone tends to create a positive bulge luminosity–density relation, which we can detect in several cases where it is not masked by the opposite observational selection effect. The latter effect is then directly reflected in the observed disk luminosity–density relation, which is indeed little influenced by the morphology–density relation.

In conclusion, we have verified that all the observed correlations which involve M_{bu} and M_d are fully

explainable as the result of observational selection, coupled with the effect of the morphology–density relation. Hence, there is no reason to invoke a primary (T-independent) influence of the environment on the bulge (or disk) luminosity in order to explain the observed correlations.

3.5 The B/D– M_B correlation

Finally, we investigate whether B/D is related to the galaxy absolute magnitude M_B , which is derived from the adopted distance and the corrected total blue apparent magnitude B_T (tabulated in RC3). To this end, we examine the B/D– M_B total correlations and (T-independent) partial correlations for all homogeneous samples and all combined samples. In this case, we also consider the type interval $T > 2$, where a strong B/D– M_B correlation was claimed by Solanes et al. (1989). Table 6 presents some results for the widest samples (SdV, K, KWO) and for relevant combined samples. A selection effect of galaxy samples is responsible for the negative T– M_B correlations which are often observed for S0+S objects: S0 are generally intrinsically fainter than early-type spirals in our samples. Moreover, the fact that late-type spirals are typically less luminous than early-type ones gives rise to the positive T– M_B correlations which are often detected for S objects. The B/D– M_B total correlation is mostly not significant, but in some cases the T– M_B correlations induce significant B/D– M_B total correlations (of opposite sign). In any case, the B/D– M_B partial correlation is never significant for homogeneous and combined samples of NBG objects (for all type intervals considered).

We repeat this correlation analysis by including in each sample also objects (with known B_T and redshift) which are not listed in NBG. For non-Virgo galaxies we simply adopt redshift-distances; for the sake of consistency with the NBG galaxy distances, members of the main body of the Virgo cluster (Virgo subclusters A and B) and of the Virgo cloud W' are given a distance of 16.8 Mpc, while members of the Virgo clouds W and M are given a distance of 35.1 Mpc. For samples enlarged to non-NBG galaxies, there is generally no B/D– M_B relation, although in some samples (the S0+S objects of the K, SdV+KWO, SdV+K samples) a negative T– M_B correlation induces a marginal B/D– M_B partial correlation (at the $< 96\%$ level only). If we repeat the analysis for the subsamples of S0 and S objects, also this weak partial correlation typically vanishes.

Therefore, it is safe to conclude that there is no good evidence that B/D is related to M_B , for a given morphological type. This conclusion is statistically well-founded especially for mid- and late-type spirals ($T > 2$.)

4 Discussion and Conclusions

Considering the role of the known morphology–density relation, from a statistical analysis of the best available B/D data sets we draw the following major conclusions:

1) The tendency of galaxies to have greater B/D with increasing local density (within the widest samples) is a reflection of the morphology–density relation, since this tendency appears to be simply due to the average decline of B/D towards later types. But this was not obvious a priori. To be more specific, when we remove the effect induced by the morphology–density relation, we find no clear evidence of a B/D dependence on the local density, at either large (\sim a few Mpc) or small (\sim a few tenths of Mpc) scales in the very nearby ($z < 0.01$) volume of the universe (The Local Supercluster).

2) Unlike previous claims, for a given morphological type, B/D is found to be substantially unrelated to the galaxy absolute magnitude (and, hence, probably to the galaxy total mass).

3) There is no need to hypothesize a primary dependence of bulge and disk luminosities on environmental density, as we note that the morphology–density relation alone tends to give rise to a greater proportion of bright bulges in denser regions (which explains some earlier claims). As a matter of fact, the growth of B/D towards earlier types appears to be mostly due to a pronounced brightening of the

bulge rather than to a dimming of the disk. Incidentally, Solanes et al.'s (1989) study of Dressler's sample yielded the opposite conclusion on the latter point. In other words, our study emphasizes that the morphology–density relation is likely to be coupled with a density segregation of bulge luminosity rather than with a segregation of disk luminosity. This point was regarded as unclear in Oemler's (1992) review.

Let us now discuss to what extent our findings differ from previous results.

Point 1 confirms the absence of primary environmental effects on B/D at small scales (of a few tenths of Mpc), in agreement with the conclusions reached by Solanes et al. (1989). On the basis of a different data set and using a two-dimensional definition of the local galaxy density, these authors clarified the (previously not well understood) role played by the morphology–density relation. Furthermore, we report the absence of (as yet unexplored) effects on B/D also at large scales (of \sim a few Mpc). Interestingly, this latter finding does not support a large-scale density segregation of bulge masses (at fixed morphological type), which has been recently hypothesized in order to try to explain the observed large-scale segregation of local low-luminosity active galactic nuclei hosted in luminous early-type spirals (see Monaco et al., 1994).

Point 2 disagrees with previous controversial claims mentioned in the introduction, which are likely to be affected by the following problems. In wide samples of mixed morphological types, a (spurious) B/D– M_B correlation may simply arise from differences in the optical luminosity functions of objects of different morphological types. These differences are especially marked between bright ellipticals, lenticulars, early spirals and later types (late spirals and irregulars) (see, e.g., Binggeli, Sandage & Tammann, 1988; Efsthathiou, Ellis & Peterson, 1988; Santiago & Strauss, 1992). This may account for the claim by Schechter & Dressler (1987), who did not use a morphological type subdivision of the objects, if in their sample early-type objects are typically more luminous than late-type ones.

But even if this subdivision is applied to Dressler's (1980a) sample (as was done by Solanes et al., 1989), two main problems remain: *i*) the presence of a number of unresolved bulges, for which Solanes et al. (1989) assumed a blue apparent magnitude of $m = 19.5$; *ii*) a severe field contamination among cluster members; in other words, a number of late-type spirals with unknown redshift could be low-luminosity foreground objects rather than bright cluster members. These problems make the B/D– M_B positive correlation claimed by the Spanish authors very doubtful.

In agreement with our view (point 3), Solanes et al. (1989) found no evidence of direct environmental effects on the bulge (or disk) luminosity by using an indirect approach. They showed that if one takes galaxy samples which are bulge-limited instead of total magnitude-limited, the luminosity–density relation (claimed in previous studies) disappears, essentially because in this way only early-type galaxies (spanning a limited type interval) are left in the sample. This is tantamount to eliminating much of the bias induced by the morphology–density relation.

However, their interpretation of the effect of morphological segregation with density is radically different. From an inspection of Dressler's sample, by indirect reasoning they argued that a decline in disk luminosities towards earlier types is the basis of the observed dependence of B/D on morphology. Consequently, in their view, the seeming tendency of B/D to increase with increasing local density is attributed to a decrease in disk luminosities rather than to an increase in bulge luminosities. The latter view is, instead, more correct even for Dressler's sample, as is readily proved by the plots presented by Lake & Carlberg (1988), who showed that B/D is much more closely related to the bulge than to the disk luminosities.

This question is important in the context of theories of galaxy formation and evolution because the mechanisms which can alter disks or bulges (see, e.g., the reviews by Evrard (1992) and Mamon (1993)) are generally different. A scenario in which bulges appear to be more affected by the environment than disks tends to favour processes occurring at galaxy formation (or at the beginning of galaxy life) — rather than late evolutionary processes — as being the major ones responsible for the morphological segregation of disk galaxies. The fact that primordial star formation rate and merger events are expected to proceed more rapidly in denser environments may be sufficient to account, at least qualitatively, for

the observed dependence of morphology and bulge luminosity on environmental density (see, e.g., Larson, 1992). A basic structural property like B/D is probably much less affected by continuing environmental effects (i.e. by the late evolutionary history of a galaxy) than other galaxy properties such as bars, arm classes, rings, tails, bridges, and gas content. Advances in the numerical simulation of galaxy formation in a cosmological context (e.g., along the lines followed by Katz (1992); Steinmetz & Müller (1993); Navarro & White (1994)) promise to yield quantitative predictions on the relative proportion of bulges and disks in galaxies.

Our results imply no appreciable total luminosity segregation with density for a given morphological type, and a slight luminosity segregation for samples of galaxies spanning a rather wide interval of morphologies (e.g., for generic samples of disk or spiral galaxies), at least within our nearby universe. In recent years, there has been a growing number of studies on redshift catalogues, which provide evidence of some total luminosity segregation (weaker than morphology segregation) for luminous galaxies (e.g., Iovino et al., 1993; Domínguez-Tenreiro, Gómez-Flechoso & Martínez, 1994) or at least for early-type luminous galaxies, whenever corrections for Galactic and internal absorptions are applied to galaxy magnitudes (e.g., Hasegawa & Umemura, 1993). There is also some evidence of diameter segregation for galaxies with large (face-on) diameters (e.g., Fang & Zou, 1994; Campos, Domínguez-Tenreiro & Yepes, G., 1994).

Wide galaxy samples with accurate, homogeneous B/D decomposition would be very valuable for further investigations into the presence of primary, subtle environmental effects, which are undetectable on the basis of the available data.

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Table 1: means, medians, and standard deviations of the B/D-distributions.

Sample	N	T	mean	s.d.	median	90% c. i.
SdV	28	-3,-2,-1	1.80	1.36	1.58	1.06 – 1.71
SdV	7	0,1	1.63	1.83	1.20	0.28 – 1.45
SdV	15	2	0.65	0.47	0.56	0.23 – 0.86
SdV	15	3	0.46	0.49	0.26	0.18 – 0.64
SdV	13	4	0.28	0.22	0.24	0.13 – 0.30
SdV	9	5	0.14	0.10	0.10	0.06 – 0.18
SdV	10	6,7	0.05	0.03	0.04	0.02 – 0.09
K	16	-3,-2,-1	3.36	2.94	1.70	0.89 – 5.25
K	14	0,1	2.16	2.86	0.88	0.54 – 2.33
K	15	2	0.81	0.90	0.52	0.18 – 0.82
K	19	3	0.28	0.31	0.18	0.08 – 0.41
K	18	4	0.17	0.23	0.09	0.05 – 0.18
K	23	5	0.12	0.17	0.03	0.02 – 0.11
K	5	6,7	0.51	1.02	0.02	0.00 – 2.33
KWO	50	-3,-2,-1	2.61	2.11	2.29	1.45 – 2.88
KWO	23	0,1	1.60	1.87	0.91	0.58 – 0.91
KWO	6	2	1.80	1.06	1.63	0.00 – 3.63
KWO	8	3	0.47	0.28	0.41	0.15 – 0.72
KWO	11	4	0.35	0.18	0.36	0.12 – 0.58
KWO	11	5	0.37	0.50	0.15	0.15 – 0.46
KWO	20	>5	0.86	1.02	0.46	0.15 – 0.72
KWO'	23	-3,-2,-1	2.42	2.10	1.82	1.45 – 2.29
KWO'	11	0,1	0.89	0.76	0.72	0.15 – 1.82
KWO'	3	2	1.15	0.59	0.91	0.00 – 1.82
KWO'	6	3	0.45	0.31	0.23	0.12 – 0.36
KWO'	7	4	0.25	0.13	0.23	0.12 – 0.36
KWO'	8	5	0.41	0.58	0.16	0.12 – 0.46
KWO'	15	>5	0.48	0.52	0.18	0.14 – 0.46
AS1	11	2,3	0.67	1.56	0.07	0.04 – 0.45
AS1	9	4	0.59	0.86	0.07	0.02 – 0.77
AS1	12	5 – 7	0.30	0.42	0.04	0.003 – 0.74
AS2	11	2,3	0.05	0.03	0.05	0.02 – 0.08
AS2	9	4	0.10	0.12	0.03	0.01 – 0.15
AS2	12	5 – 7	0.26	0.78	0.03	0.004 – 0.04

Table 2: the B/D- ρ_σ , T- ρ_σ correlations for the homogeneous samples.

Sample	N	Variables	r_s	r_k	r
SdV (S0+S)	94	B/D- $\rho_{0.5}$	0.263 (99.5)	0.185 (99.6)	0.035 (<90.)
SdV (S0+S)	94	T- $\rho_{0.5}$	-0.358 (99.98)	-0.253 (99.99)	
KWO (S0+S)	100	B/D- $\rho_{0.5}$	0.249 (99.4)	0.173 (99.5)	0.075 (<90.)
KWO (S0+S)	100	T- $\rho_{0.5}$	-0.324 (99.95)	-0.231 (99.97)	
KWO' (S0+S)	56	B/D- $\rho_{0.5}$	0.337 (99.4)	0.230 (99.4)	0.154 (96.8)
KWO' (S0+S)	56	T- $\rho_{0.5}$	-0.299 (98.7)	-0.222 (99.2)	
K (S0+S)	59	B/D- $\rho_{0.5}$	0.055 (<90.)	0.044 (<90.)	—
K (S0+S)	59	T- $\rho_{0.5}$	-0.021 (<90.)	-0.018 (<90.)	

Table 3: the B/D- ρ_σ , T- ρ_σ correlations for the combined samples.

Sample	N	Variables	r_s	r_k	r
SdV+K (S0+S)	141	B/D- $\rho_{0.5}$	0.233 (99.7)	0.161 (99.8)	0.067 (<90.)
SdV+K (S0+S)	141	T- $\rho_{0.5}$	-0.276 (99.95)	-0.195 (99.97)	
SdV+KWO (S0+S)	175	B/D- $\rho_{0.5}$	0.256 (99.97)	0.180 (99.98)	0.062 (<90.)
SdV+KWO (S0+S)	175	T- $\rho_{0.5}$	-0.309 (>99.99)	-0.216 (>99.99)	
SdV+KWO' (S0+S)	139	B/D- $\rho_{0.5}$	0.230 (99.7)	0.159 (99.7)	0.066 (<90.)
SdV+KWO' (S0+S)	139	T- $\rho_{0.5}$	-0.251 (99.9)	-0.178 (99.9)	

Table 4: the B/D- D_v , T- D_v correlations.

Sample	N	Variables	r_s	r_k	r
SdV (S0+S)	94	B/D- D_v	-0.136 (90.4)	-0.091 (90.4)	-0.020 (<90.)
SdV (S0+S)	94	T- D_v	0.175 (95.4)	0.121 (95.8)	
KWO (S0+S)	100	B/D- D_v	-0.198 (97.6)	-0.139 (98.0)	-0.051 (<90.)
KWO (S0+S)	100	T- D_v	0.291 (99.8)	0.202 (99.9)	
KWO' (S0+S)	56	B/D- D_v	-0.103 (<90.)	-0.071 (<90.)	—
KWO' (S0+S)	56	T- D_v	0.152 (<90.)	0.102 (<90.)	
K (S0+S)	59	B/D- D_v	-0.091 (<90.)	-0.059 (<90.)	—
K (S0+S)	59	T- D_v	0.082 (<90.)	0.049 (<90.)	
SdV+K (S0+S)	141	B/D- D_v	-0.150 (96.2)	-0.101 (96.3)	-0.042 (<90.)
SdV+K (S0+S)	141	T- D_v	0.176 (98.2)	0.121 (98.4)	
SdV+KWO (S0+S)	175	B/D- D_v	-0.163 (98.5)	-0.112 (98.6)	-0.027 (<90.)
SdV+KWO (S0+S)	175	T- D_v	0.212 (99.8)	0.149 (99.8)	
SdV+KWO' (S0+S)	139	B/D- D_v	-0.068 (<90.)	-0.046 (<90.)	—
SdV+KWO' (S0+S)	139	T- D_v	0.090 (<90.)	0.061 (<90.)	

Table 5: the $M_{bu}-\rho_\sigma$, $M_d-\rho_\sigma$ correlations.

Sample	N	Variables	r_s	r_k	r
SdV (S0+S)	94	$M_{bu} - \rho_{0.5}$	-0.176 (95.5)	-0.132 (97.0)	-0.049 (<90.)
SdV (S0+S)	94	$M_{bu} - \rho_{1.0}$	-0.218 (98.3)	-0.157 (98.8)	-0.081 (<90.)
SdV (S0+S)	94	$M_d - \rho_{0.5}$	0.123 (<90.)	0.080 (<90.)	0.022 (<90.)
SdV (S0+S)	94	$M_d - \rho_{1.0}$	0.072 (<90.)	0.040 (<90.)	-0.019 (<90.)
SdV (S0+S)	94	$M_d - \rho_{2.0}$	-0.009 (<90.)	-0.002 (<90.)	-0.064 (<90.)
KWO (S0+S)	100	$M_{bu} - \rho_{0.5}$	-0.175 (95.9)	-0.122 (96.4)	-0.037 (<90.)
KWO (S0+S)	100	$M_{bu} - \rho_{1.0}$	-0.122 (<90.)	-0.077 (<90.)	0.021 (<90.)
KWO (S0+S)	106	$M_d - \rho_{0.5}$	0.140 (92.4)	0.087 (90.7)	0.076 (<90.)
KWO (S0+S)	106	$M_d - \rho_{1.0}$	0.186 (97.2)	0.125 (97.2)	0.115 (96.3)
KWO (S0+S)	106	$M_d - \rho_{2.0}$	0.241 (99.4)	0.160 (99.3)	0.151 (98.8)
KWO (S0+S) D<25Mpc	93	$M_d - \rho_{2.0}$	0.085 (<90.)	0.059 (<90.)	0.052 (<90.)
KWO' (S0+S)	56	$M_{bu} - \rho_{0.5}$	-0.175 (90.1)	-0.129 (91.9)	-0.057 (<90.)
KWO' (S0+S)	56	$M_{bu} - \rho_{1.0}$	-0.129 (<90.)	-0.078 (<90.)	-0.007 (<90.)
KWO' (S0+S)	91	$M_d - \rho_{0.5}$	0.091 (<90.)	0.056 (<90.)	0.057 (<90.)
KWO' (S0+S)	91	$M_d - \rho_{1.0}$	0.139 (90.5)	0.097 (91.4)	0.100 (93.2)
KWO' (S0+S)	91	$M_d - \rho_{2.0}$	0.194 (96.7)	0.129 (96.5)	0.131 (97.0)
KWO' (S0+S) D<25 Mpc	78	$M_d - \rho_{2.0}$	0.053 (<90.)	0.038 (<90.)	0.041 (<90.)

Table 6: the B/D- M_B , T- M_B correlations.

Sample	N	Variables	r_s	r_k	r
SdV (S0+S)	94	B/D- M_B	0.076 (<90.)	0.053 (<90.)	-0.079 (<90.)
SdV (S0+S)	94	T- M_B	-0.230 (98.7)	-0.179 (99.5)	
SdV (S)	67	B/D- M_B	-0.102 (<90.)	-0.069 (<90.)	–
SdV (S)	67	T- M_B	0.015 (<90.)	-0.003 (<90.)	
KWO (S0+S)	100	B/D- M_B	0.110 (<90.)	0.082 (90.8)	–
KWO (S0+S)	100	T- M_B	-0.050 (<90.)	-0.048 (<90.)	
KWO (S)	59	B/D- M_B	0.083 (<90.)	0.055 (<90.)	0.102 (<90.)
KWO (S)	59	T- M_B	0.211 (94.6)	0.152 (95.5)	
KWO' (S0+S)	56	B/D- M_B	0.027 (<90.)	0.016 (<90.)	–
KWO' (S0+S)	56	T- M_B	-0.041 (<90.)	-0.056 (<90.)	
KWO' (S)	38	B/D- M_B	-0.043 (<90.)	-0.035 (<90.)	-0.005 (<90.)
KWO' (S)	38	T- M_B	0.295 (96.4)	0.205 (96.5)	
K (S0+S)	59	B/D- M_B	-0.126 (<90.)	-0.092 (<90.)	–
K (S0+S)	59	T- M_B	-0.111 (<90.)	-0.066 (<90.)	
K (S)	51	B/D- M_B	-0.115 (<90.)	-0.084 (<90.)	
K (S)	51	T- M_B	-0.177 (<90.)	-0.113 (<90.)	
SdV+K (S0+S)	141	B/D- M_B	0.019 (<90.)	0.021 (<90.)	-0.069 (90.3)
SdV+K (S0+S)	141	T- M_B	-0.195 (99.0)	-0.143 (99.4)	
SdV+K (S)	109	B/D- M_B	-0.135 (91.8)	-0.084 (90.1)	–
SdV+K (S)	109	T- M_B	-0.046 (<90.)	-0.036 (<90.)	
SdV+KWO (S0+S)	175	B/D- M_B	-0.002 (<90.)	0.002 (<90.)	-0.072 (91.5)
SdV+KWO (S0+S)	175	T- M_B	-0.115 (93.5)	-0.095 (96.9)	
SdV+KWO (S)	117	B/D- M_B	-0.173 (96.9)	-0.115 (96.7)	-0.056 (<90.)
SdV+KWO (S)	117	T- M_B	0.171 (96.7)	0.115 (96.7)	
SdV+KWO' (S0+S)	139	B/D- M_B	-0.024 (<90.)	-0.017 (<90.)	–
SdV+KWO' (S0+S)	139	T- M_B	-0.071 (<90.)	-0.068 (<90.)	
SdV+KWO' (S)	98	B/D- M_B	-0.158 (94.0)	-0.108 (91.3)	-0.035 (<90.)
SdV+KWO' (S)	98	T- M_B	0.220 (98.5)	0.142 (98.1)	

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Figure Captions

Fig. 1: plot of the median values of B/D , together with the associated 90% confidence intervals, for different morphological type intervals (as reported in Table 1). The values relative to the SdV, K, KWO, and KWO' samples are denoted by circles, crosses, triangles, and squares, respectively.

Fig. 2: plot of the $B/D-\rho_{0.5}$ correlation for the S0+S objects of the SdV sample. The lenticulars, early-type spirals, and late-type spirals ($T>3$) are denoted by open circles, crosses, and dots, respectively.

Fig. 3: plot of the $B/D-\rho_{0.5}$ correlation for the S0+S objects of the KWO sample. Symbols as in Fig. 2

Fig. 4: plot of the $B/D-D_v$ correlation for the S0+S objects of the KWO sample. Symbols as in Fig. 2.